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EXPERIMENTAL STUDIES WITH AN ACTIVE MAGNETIC REGENERATING REFRIGERATOR

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ABSTRACT

Experimental results for an active magnetic regenerator (AMR) are presented. The focus is on whether or not it pays off to partly substitute soft magnetic material with non-magnetic insulation in a flux-conducting core in the magnet system. Such a substitution reduces losses due to heat conduction and eddy currents, but also reduces the magnetic field. Two different cores were tested in the AMR system with different cooling loads and it is shown, that in the present case, replacing half of the iron with insulation lead to an average reduction in temperature span of 14%, but also a small decrease in *COP*, hence the substitution did not pay off. Furthermore, it is shown experimentally, that small imbalances in the heat transfer fluid flow greatly influence the system performance. A reduction of these imbalances through valve adjustments resulted in an increase in the temperature span from approximately 16 K to 27.3 K.

1. INTRODUCTION

Magnetic refrigeration is a solid state refrigeration technology that is a potential replacement for vapour compression in near-room-temperature applications. Cooling is based on the magnetocaloric effect in the solid refrigerant. The magnetocaloric effect causes the material to heat up when magnetised and cool down when demagnetised when ferromagnetic refrigerants are used. The effect is reversible in many materials and therefore may be used to construct an efficient cooling cycle. A water-based heat transfer fluid is used to transfer heat from the solid refrigerant to the external heat exchangers used to absorb a cooling load and to reject heat to the ambient. Because the fluid is single phase, superheat and throttling losses are avoided. Magnetocaloric materials (MCMs) are an active research topic and several families of materials that are well-suited to air conditioning and refrigeration applications have been identified, see e.g. Pecharsky *et al.* (2006). Because the temperature change of known materials when magnetised in a strong permanent magnet is much lower than the operating temperature span of a practical cooling device, MCMs are implemented in a regenerative cycle such as the active magnetic regenerator (AMR) cycle. In the AMR cycle, a porous MCM regenerator with an entrained heat transfer fluid is put in thermal contact with hot and cold thermal reservoirs. The cycle consists of four processes: first the MCM is magnetised causing its temperature to increase. Then the heat transfer fluid is pumped from the cold reservoir to the hot reservoir and heat is rejected to the ambient while the MCM is cooled. The MCM is then demagnetised and its temperature decreases. Finally, fluid is pumped from the hot reservoir to the cold where a cooling load is absorbed. The MCM is warmed by the fluid flow and the system returns to its original temperature.

Experimental AMRs have been demonstrated in a range of configurations and applications (Kitanovski *et al.* 2015). Some of the first devices used superconducting electromagnets (Zimm *et al.* 1998) but more recent devices have used more practical permanent magnets. Recent work on AMR devices has focused on making more compact devices by increasing the operating frequency of the device (Tura 2011) and on increasing the efficiency (Lozano *et al.* 2013). An AMR developed for electronics cooling produced a cooling power of 2.5 kW at an 11 K temperature span (Jacobs *et al.* 2014). Our group presented a rotating AMR using Gd as a refrigerant that produced 100 W at a span of 20.5 K (Engelbrecht *et al.* 2012). Analysis performed on this device (Lozano *et al.*, 2013) showed that the system suffered reduced performance from heat leaks to the cold reservoir and to the regenerator, drivetrain losses and friction losses in the valve system. This paper presents a newly developed device designed to reduce losses compared to the previously reported device in

order to improve efficiency. The effects of heat leaks through parts of the magnet system and eddy current losses are investigated experimentally by building a composite magnet core with lower thermal and electrical conductivity and comparing results to those with a solid iron magnet core. Finally, the effect of variations in the fluid flow in individual regenerator beds is studied and the effect of adjusting the flow in each bed is quantified at a specific operating condition. The temperature span, cooling power, and *COP* of the new device are given for a range of operating conditions.

2. DESCRIPTION OF THE AMR DEVICE

The AMR device presented here is designed for better regenerator performance, improved thermal isolation, reduced friction and better drivetrain efficiency. The goal is to demonstrate a *COP* that is significantly higher than our group's previously presented device while still producing a practical temperature span and cooling power. The AMR consists of 11 independent regenerator beds that are stationary and arranged in an annulus. The regenerator housing is a thin sheet of stainless steel and an air gap at the inner and outer diameters acts as thermal insulation. The magnetic field is provided by 1.5 L of permanent NdFeB magnet in a rotating Halbach-like assembly mounted on the outer diameter of the regenerator and a stationary soft magnetic core mounted on the inner diameter of the regenerator. The magnet assembly consists of two high field regions and two low field regions, meaning that each rotation of the magnet gives two full AMR cycles in each regenerator bed. A summary of the materials used to construct the regenerator is given in Table 1. A photo of the assembled device is shown in Fig. 1. The magnet is rotated by an electric motor with a gear drive and fluid flow is provided by a single pump operating continuously. The timing and fluid flow direction is controlled by the fluid flow system, which is explained in detail in Section 4.



Figure 1. Photo of the AMR device assembled. Tubes at the top of the regenerator are to and from the pump and the gear drive is shown.

Table 1. Summary of regenerator materials

Layer	Material	Mass	Curie temperature	Sphere diameter
1	Gd	0.71 kg	291 K	0.5-0.6 mm
2	Gd97.5Y2.5	0.20 kg	287 K	0.3-0.5 mm
3	Gd95Y5	0.39 kg	283 K	0.3-0.5 mm
4	Gd90Y10	0.41 kg	272 K	0.3-0.5 mm
Total		1.70 kg		

3. MAGNET CORE

The magnet core is used to guide magnetic flux from the permanent magnets to reduce the total reluctance of the magnetic circuit and to give the desired magnetic field profile in the gap where the regenerator is mounted. However, the core will also act as a thermal short circuit between the hot and cold reservoirs, causing energy that could be used for cooling to be conducted instead to the hot reservoir. Finally, the fluctuating magnetic field in the magnet core will cause some eddy current heating inside the core, which will increase motor work and decrease *COP*. Eddy currents scale with the squared size of the material perpendicular to the magnetic field, the fluctuations in the magnetic field and with the electrical conductivity of the material. The effects of eddy current heating, axial thermal conductivity and permeability on AMR performance are studied here by testing the device using two different magnet cores. The composite core was constructed of alternating 2 mm thick disks of iron and fiberglass and bonding them with epoxy. The composite core has lower electrical and thermal conductivities in the axial direction and a lower average magnetic permeability. It will reduce eddy currents and thermal losses through the magnet core but will also reduce the strength of the magnetic field, which will reduce the magnetocaloric effect in the regenerator. The iron core was constructed of 2 mm thick iron disks bonded with epoxy. The iron core will have a higher magnetic field while generating more eddy currents and having increased heat losses due to thermal conduction.

3.1. Magnetic field profile for both magnet cores

The measured magnetic field in the middle of the gap where the regenerator is mounted is shown in Fig. 2. The figure shows that the maximum field is approximately 18% higher for the iron core and the low field region is closer to 0 T. The magnetocaloric effect in the regenerator will be higher when using the iron core, which will result in better heat transfer between the heat transfer fluid and the MCM. Loss mechanisms such as Eddy current heating and axial heat losses will be lower for the composite core.

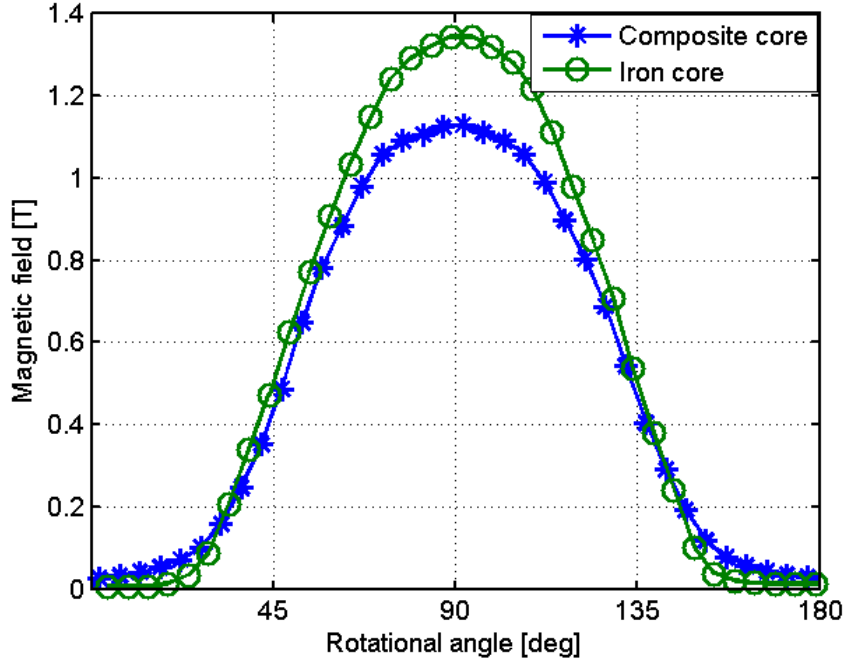


Figure 2. Measured magnetic field with the composite and iron core installed in the magnet assembly. Measurement uncertainties are less than 0.5 %.

3.2. AMR experiments with the two cores

A number of AMR experiments have been carried out with each of the two cores mounted in the system. Figure 3 shows the applied cooling power and achieved COP for a series of such experiments. In all cases the system was operated at an AMR frequency of 0.7 Hz and a heat transfer fluid flow rate of approximately 3.2 L/min. The COP was evaluated as

$$COP = \frac{\dot{Q}_L}{\dot{W}_{motor} + \Delta p_{reg} \cdot \dot{V}} \quad (1)$$

where

\dot{Q}_L = applied cooling load [W], \dot{W}_{motor} = electrical power supplied to motor [W], Δp_{reg} = pressure drop over regenerator [Pa], \dot{V} = volumetric flow rate [m³ s⁻¹]. Measurement uncertainties for these parameters are given in Table 2.

Thus, the efficiency of the pump itself was not included in the calculation since this component was highly over dimensioned in order to be able to cover a broad range of experimental conditions. In the considered series of experiments, three different cooling loads were applied when the composite core was mounted. After replacement with the iron core, the experiments were repeated with the same cooling loads. It is clear from Figure 3, that for all three cooling loads the achieved temperature span was higher with the iron core than with the composite core with an average increase of 14 %. However, it can also be seen that there is an almost linear relationship between temperature span and COP for both cores. Furthermore, the COP at a given temperature span is consistently higher with the iron core, but the difference is small, which is also evident by the fact that the average 2nd law efficiency only increased by 3.7 % by going from the composite to the iron core.

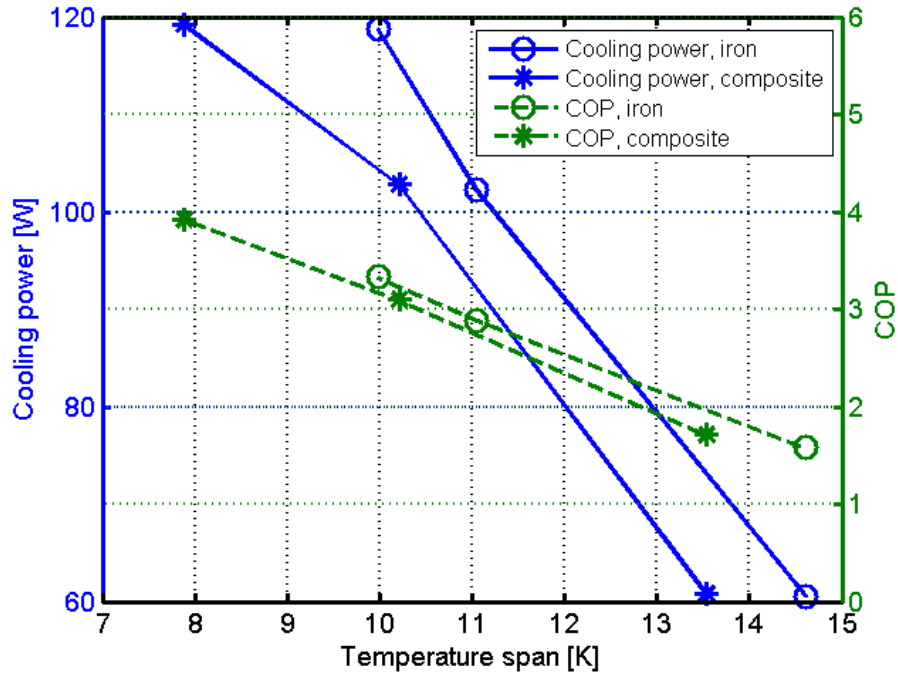


Figure 3. Steady state AMR results with the two different cores.

The adiabatic temperature change, ΔT_{ad} , which is the temperature increase that takes place in a magnetocaloric material when a certain magnetic field is applied to it under adiabatic conditions, is often used to characterize the material. In general, ΔT_{ad} increases with increasing field, which also increases heat transfer between the MCM and the heat transfer fluid. In the present case this explains why the temperature span increased when the composite core was replaced with the iron core leading to a higher maximum field. The fact that the COP at a given temperature span, and hence the 2nd law efficiency, increased only slightly, may be attributed to the losses due to increased axial conduction in the core. In order to get an indication of the influence of the eddy current losses, an experiment was performed by rotating the magnet without the regenerator mounted. A thermocouple was mounted in good thermal contact with the core and the motor power was recorded as a function of rotational speed. This was done for both of the cores and resulted in no significant temperature increase or change in motor power as would have been expected if significant eddy current losses were present. All in all the results indicate, that in the present case it does not pay off to trade maximum magnetic field for insulating material in the core. It should however be noted, that the investigated system includes an insulating air gap between core and regenerator housing, see Eriksen *et al.* (2015) which breaks the heat conduction path, and without which the axial conduction in the core would have been expected to play a more significant role. Finally it should be noted, that the described AMR experiments have revealed significant sources of uncertainty in the AMR results originating from the fluid flow system, which has motivated investigations described below.

Table 2. Measurement uncertainties

Temperature span	Pressure drop	Flow rate	AMR Frequency	Cooling power	Motor power
0.2 K	0.2 %	2 %	0,5 %	0,05%	0,05%

4. FLOW CONTROL

The exact adjustment of the flow control system has proven to play a key role to the system performance. This section presents experiments showing the effect of such adjustments.

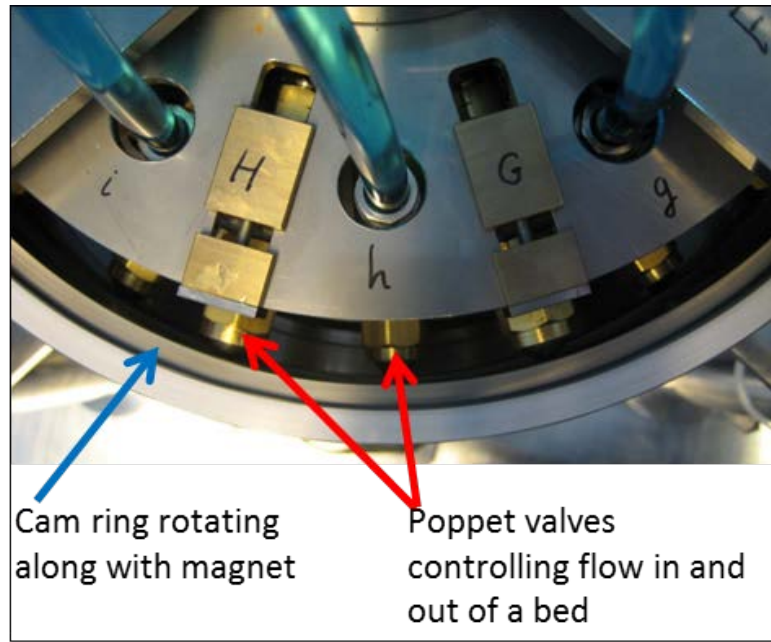


Figure 4. Poppet valves actuated by cam rings controlling flow in and out of the hot side of regenerator beds.

Each regenerator bed is connected to two poppet valves controlling the flow in and out of the hot side, respectively. The valves are actuated by a dedicated cam ring for each of the two flow directions. Each ring has two cams corresponding to two AMR cycles per revolution of the two pole magnet with which they rotate. At the cold side of the regenerator, a compact manifold with check valves ensures a unidirectional flow through an electrical heater where a heat load can be applied. For a detailed description of the flow system, see Eriksen *et al.* (2015).

4.1. Flow balancing experiments

A portable flow meter (Omega Microflow TFB322D) was connected in series with the poppet valve supplying fluid to an arbitrarily chosen bed. Without rotating the magnet/cam rings, the pump was turned on and the flow rate of the fluid entering the chosen bed was measured. Next, the magnet/cam rings were incrementally rotated one degree at a time, and for each position the flow rate was measured. This was repeated until the flow profiles corresponding to the two cams on the ring controlling the hot to cold blows (“In, cam1” and “In, cam 2” in Figure 5a) were mapped out. The procedure was repeated with the flow meter connected in series with the poppet valve controlling the flow out of the hot side of the bed and the flow profiles of the cold to hot blows (“Out, cam1” and “Out, cam 2” in Figure 5a) were measured.

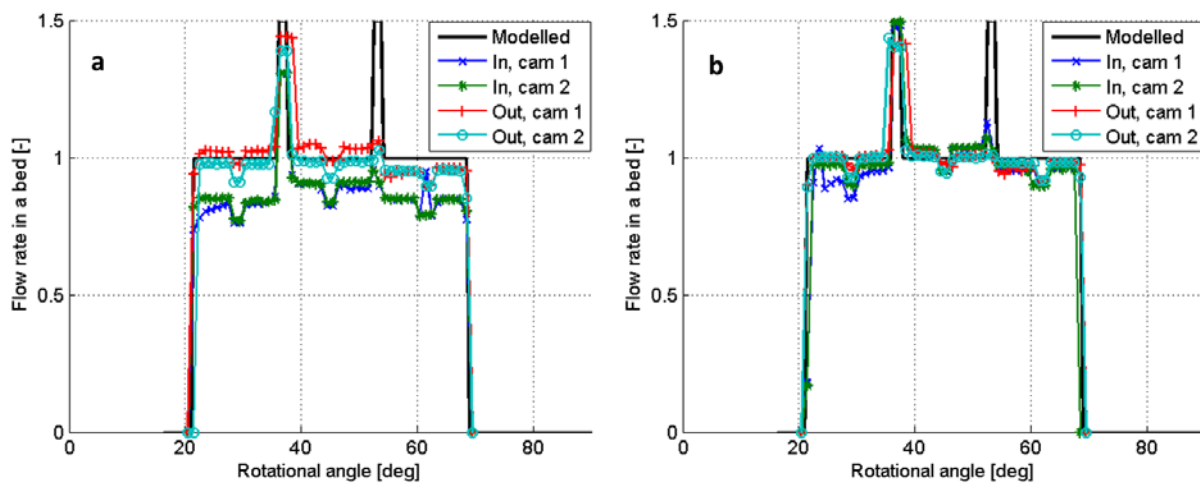


Figure 5. Flow profiles normalized with model predictions measured for both cams on each of the two cam rings controlling flow in and out of a regenerator bed before adjustment (a) and after adjustment (b).

In Figure 5 the flow profiles are plotted together with a theoretical flow profile based on the assumption of a constant volumetric flow rate in the entire system, which is divided between the individual beds depending on the degree of opening of all the poppet valves. The figure represents stationary operation of the flow system and the actual flow profile may be slightly different under dynamic operating conditions. The assumption of a constant overall flow rate is based on the use of a gear pump and verified by a flow meter (Omega FMG71) in the main flow circuit. It can be seen, that there is a good agreement between the shape of the measured and the theoretical flow profiles. However, there is a discrepancy between the cold to hot blow and the hot to cold blow of 14.5 % on average, indicating a higher flow resistance in the hot to cold direction. To compensate for this, a simple ball valve in series with the poppet valve controlling the flow in the cold to hot direction in the considered bed was partially closed to even out this difference, resulting in the flow profiles in figure 5b. To investigate the effect of this adjustment, an AMR experiment was conducted with a frequency of 0.63 Hz and a flow rate of 2.48 L min^{-1} . After reaching steady state at a temperature span of 19.8 K, the adjustment was eliminated by fully reopening the ball valve. This resulted in a rather dramatic decrease in the temperature span which dropped approximately 3.4 K down to 16.4 K, see Figure 6.

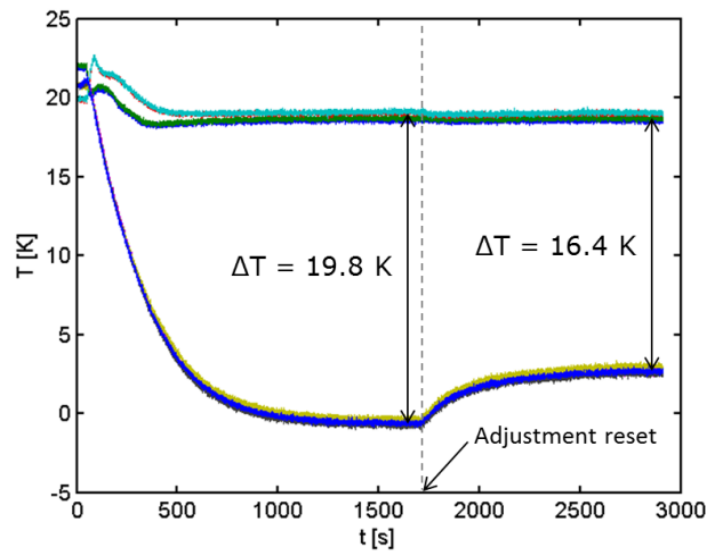


Figure 6. Hot and cold side temperatures during an AMR experiment showing the effect of adjusting the flow resistance in one out of the eleven regenerator beds.

4.2. Future work

The fact that the described adjustment of the flow rate in only one arbitrarily chosen bed had such a significant impact on the system performance motivates a more thorough investigation of this effect. From an earlier characterization of the eleven beds conducted with a single blow test setup, it is known that some variation in flow resistance from bed to bed is present. For a flow rate of 2.22 L min^{-1} the standard deviation in the flow resistance of the 11 beds was 5.9 % of the mean value of $56.7 \text{ kPa min L}^{-1}$. A hypothesis of the authors is, that this variation in bed flow resistances is responsible for the direction dependent flow rates observed in the experiment described above due to the way the beds are connected to each other during operation, and that this effect may be minimized by ensuring a more uniform flow resistance of all the beds through valve adjustments. This will be investigated in future work, but at the time of writing such an adjustment has increased the temperature span from approximately 16 K to 27.3 K at a frequency of 1 Hz and a flow rate of 3 L min^{-1} . The effect of the adjustments on other system performance metrics such as cooling power and *COP* will also be quantified.

5. CONCLUSIONS

An experimental study investigating the effect of replacing soft magnetic material with thermal and electrical insulation in the flux conducting core of the magnet assembly in an AMR device has been carried out. Two different cores were used, both made by stacking 2 mm layers of iron glued together with electrically

insulating epoxy. One of the cores was made as a composite where every second iron layer was replaced with glass fibre acting as insulation. The scope was to investigate the effect of losses due to axial conduction and eddy currents in the core and evaluate the influence of reducing these losses at the expense of a reduction in the magnetic field in the regenerator. The study has shown a significant decrease of the temperature span for fixed cooling loads with the composite core which is attributed to the reduced magnetic field. Even though the difference in *COP* was small, the iron core also proved to be superior in terms of efficiency. The effect of the eddy current losses has proven to be small and the effect of axial heat conduction in the core is limited by the insulating air gap between core and regenerator. It is concluded, that in the present case, optimizing the magnetic field with the iron core is more important than limiting its thermal and eddy current losses by laminating it with insulating material. Furthermore it is shown through experiments, that small variations in the flow resistances of the beds drastically limit the performance of the system. A first attempt of balancing out these resistances has led to an increase in temperature span from approximately 16 K to 27.3 K for a given set of operating conditions.

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